

Cosmic rays: extragalactic and Galactic

Ya. N. Istomin^{a,b}

^a*P. N. Lebedev Physical Institute, Leninsky Prospekt 53, Moscow, 119991 Russia*

^b*Moscow Institute Physics and Technology, Institutskii per. 9, Dolgoprudnyi, Moscow region, 141700 Russia*

Abstract

From the analysis of the flux of high energy particles, $E > 3 \cdot 10^{18} \text{eV}$, it is shown that the distribution of the power density of extragalactic rays over energy is of the power law, $\bar{q}(E) \propto E^{-2.7}$, with the same index of 2.7 that has the distribution of Galactic cosmic rays before so called 'knee', $E < 3 \cdot 10^{15} \text{eV}$. However, the average power of extragalactic sources, which is of $\mathcal{E} \simeq 10^{43} \text{erg s}^{-1}$, at least two orders exceeds the power emitted by the Galaxy in cosmic rays, assuming that the density of galaxies is estimated as $N_g \simeq 1 \text{Mpc}^{-3}$. Considering that such power can be provided by relativistic jets from active galactic nuclei with the power $\mathcal{E} \simeq 10^{45} - 10^{46} \text{erg s}^{-1}$, we estimate the density of extragalactic sources of cosmic rays as $N_g \simeq 10^{-2} - 10^{-3} \text{Mpc}^{-3}$. Assuming the same nature of Galactic and extragalactic rays, we conclude that the Galactic rays were produced by a relativistic jet emitted from the Galactic center during the period of its activity in the past. The remnants of a bipolar jet are now observed in the form of bubbles of relativistic gas above and below the Galactic plane. The break, observed in the spectrum of Galactic rays ('knee'), is ex-

Email address: istomin@lpi.ru (Ya. N. Istomin)

plained by fast escape of energetic particle, $E > 3 \cdot 10^{15} eV$, from the Galaxy because of the dependence of the coefficient of diffusion of cosmic rays on energy, $D \propto E^{0.7}$. The obtained index of the density distribution of particles over energy, $N(E) \propto E^{-2.7-0.7/2} = E^{-3.05}$, for $E > 3 \cdot 10^{15} eV$ agrees well with the observed one, $N(E) \propto E^{-3.1}$. Estimated time of termination of the jet in the Galaxy is $4.2 \cdot 10^4$ years ago.

Keywords: cosmic rays, the Galaxy, galaxies: active

PACS: 98.70.Sa

1. Introduction

The main hypothesis of the origin of cosmic rays in the Galaxy is the acceleration of charged particles to high energies on the fronts of shock waves formed by supernova explosions. To ensure the power of cosmic rays, observed in the Galaxy, which equals about $10^{41} erg\ s^{-1}$, it is necessary to transform to accelerated particles about 15% of the kinetic energy of expanding shock waves. These strong shocks produce the universal spectrum of particle energy distribution, $N(E) \propto E^{-2}$. This allows to put together cosmic rays originating from different supernova, and forms the unique particle spectrum, extending from energies in a few units of GeV to energies $\simeq 10^{18} eV$. The observed spectrum $N(E)$ significantly differs from universal, that is explained by the propagation of cosmic rays in the Galaxy. It has the character of diffusion in space because of the scattering of charged particles by magnetic field inhomogeneities. The diffusion coefficient increases with particle energy, i.e. the lifetime of the fast particles in the Galaxy decreases. Therefore, the observed spectrum over energy differs

from the spectrum given by sources, remaining a power law, $N(E) \propto E^{-\beta}$. But the value of β is not constant, it changes from $\beta_1 = 2.7$ for $E < 3 \cdot 10^{15} eV$ to $\beta_2 = 3.1$ for $E > 3 \cdot 10^{15} eV$. The important circumstance is the fact that the spectrum at high energies becomes softer, not harder. This suggests that the source of cosmic rays at energies $E < 3 \cdot 10^{15} eV$ and at energies $E > 3 \cdot 10^{15} eV$ is single. It is possible the superposition of two independent sources, if it would be vice versa, $\beta_2 < \beta_1$. But it is unlikely that the spectrum produced by one source at $E < 3 \cdot 10^{15} eV$ would cut off at higher energies, whereas another independent source at energies $E > 3 \cdot 10^{15} eV$ would cut off at lower energies, and they were joined at the same energy $E \simeq 3 \cdot 10^{15} eV$.

If the source is single, it would produce cosmic rays also in other galaxies with characteristics similar to those observed in the Galaxy. The aim of our work is to analyze the properties of cosmic rays of superhigh energies $E > 3 \cdot 10^{18} eV$ observed on the Earth, coming outside, from other galaxies, and compare them with the properties of Galactic cosmic rays.

2. Ultrahigh energy cosmic rays

The energy distribution of the flux of cosmic rays $I(E)$ observed on the Earth at energies $E > 3 \cdot 10^{18} eV$ noticeably deviates from the power law distribution, which is typical for lower energies, $3 \cdot 10^{15} eV < E < 3 \cdot 10^{18} eV$, where $I(E) \propto E^{-3.1}$. This region is called 'ankle', here cosmic rays of Galactic origin are replaced by particles, the origin of which has extragalactic nature. They come from active galaxies located at large distances. In particular, there is

identification of coming particles with energies $E \simeq 10^{19} \text{eV}$ from galaxy Cen A, located at distance 4.6Mpc (Auger Collaboration, 2010), and correlation with active galactic nuclei (AGN) within $\simeq 100 \text{Mpc}$ (Auger Collaboration; 2007, 2008). Charged particles (protons or nuclei) of such energy, $\simeq 10^{19} \text{eV}$, have large cyclotron radius r_L in intergalactic magnetic field $B \simeq 10^{-9} \text{G}$,

$$r_L = \frac{E}{ZeB} = 11Z^{-1} \left(\frac{E}{10^{19} \text{eV}} \right) \left(\frac{B}{1 \text{nG}} \right)^{-1} \text{Mpc}.$$

The magnetic field changes its direction on the scale of the order of 1Mpc , i.e. correlation length of magnetic field equals $l_c \simeq 1 \text{Mpc}$. As a result a charged particle moving to our Galaxy, walking distance r , deviates from the initial direction on the angle $\Delta\theta$,

$$\Delta\theta = \left(\frac{l_c r}{r_L^2} \right)^{1/2} = 0.09Z \left(\frac{E}{10^{19} \text{eV}} \right)^{-1} \left(\frac{B}{1 \text{nG}} \right) \left(\frac{l_c}{1 \text{Mpc}} \right)^{1/2} \left(\frac{r}{1 \text{Mpc}} \right)^{1/2}.$$

Therefore, the propagation of cosmic rays of high energy from sources, that are closer than $r < 100 \text{Mpc}$, can be considered as rectilinear in a good approximation, while from more distant sources as diffusive. Let us find the distribution function $N(t, \mathbf{r}, E)$ of cosmic rays of high energy, $E \simeq 10^{19} \text{eV}$, over the space \mathbf{r} and the energy E , considering that charged particles come to the given point from many sources in space located at points of $\mathbf{r} = \mathbf{r}_i$ and having powers $Q_i(E)$. Considering the distribution of sources in space as homogeneous in average, the particle distribution function of N can be considered as isotropic, depending only on the distance r . In addition, due to the large number of sources, the particle distribution also can be considered stationary, $N = N(r, E)$. We discuss two cases: rectilinear and diffusive propagation of particles.

2.1. Rectilinear motion

In this case, the equation for the distribution function of cosmic rays has the form

$$-c \frac{\partial N}{\partial r} + \frac{\partial}{\partial E} \left(\frac{dE}{dt} N \right) = \sum_i \frac{Q_i(E)}{4\pi r_i^2} \delta(r - r_i). \quad (1)$$

Here c is the velocity of the light, $\delta(x)$ is the Dirac delta function. The value of dE/dt is energy losses of particles. They consist of two parts: losses connected with the interaction of energetic particles with the relict radiation and losses associated with the expansion of the Universe. To the first, it is the so called GZK effect (Greizen, 1966; Zatsepin & Kuz'min, 1966) - pion production in the reaction $p + \gamma \rightarrow N + \pi$. The characteristic particle energy of this process is $E_\pi = \mu c^2(1 + \mu/m_p)m_p c^2/2T \simeq 4 \cdot 10^{20} eV$ (m_p is the mass of the proton, μ is the mass of the muon, T the temperature of the relict radiation). The interaction of a proton with a photon produces a neutral π -meson, the interaction of a photon with a nucleus can produce also charged π -mesons. At lower energies there becomes significant the generation of electron-positron pairs, $p + \gamma = p + e^+ + e^-$. The characteristic particle energy of this reaction is $E_e = m_e c^2 m_p c^2 / T \simeq 2.1 \cdot 10^{18} eV$ (m_e is the electron mass). Energy losses in photo-pion reactions are well described by the expression (Stanev et al., 2000)

$$\left(\frac{d\epsilon}{dt'} \right)_\pi = -(1 + \epsilon) \exp(-\epsilon^{-1}). \quad (2)$$

Here we introduced the dimensionless energy $\epsilon = E/E_\pi = E/4 \cdot 10^{20} eV$ and the dimensionless time $t' = ct/L$, where L is the characteristic distance, passing which a particle loses the energy of the order of its initial value, $L = 13.7 Mpc$.

Distances conveniently to measure in the same units, $r' = r/L$. The energy losses due to the generation of electron-positron pairs (see the paper by Berezhinsky, Gazizov & Grigorieva, 2006) can be described approximately by the expression

$$\left(\frac{d\epsilon}{dt'}\right)_e = -a\epsilon(\epsilon_e^{-2} + b\epsilon_e^{0.6})^{-1} \exp(-\epsilon_e^{-1}), \quad \epsilon_e = E/E_e = 190\epsilon. \quad (3)$$

Here the constants a and b are $a = 4.5 \cdot 10^{-4}$, $b = 8.4 \cdot 10^{-3}$ correspondingly. Adiabatic particle losses associated with the general expansion of the Universe are described by the Hubble law, $dE/dt = -HE$, where H is the Hubble constant, $H = 72 \text{ km s}^{-1}/\text{Mpc}$. In dimensionless variables adiabatic losses are

$$\left(\frac{d\epsilon}{dt'}\right)_a = -\alpha\epsilon, \quad \alpha = 3.3 \cdot 10^{-3}. \quad (4)$$

Here it should be noted that the Hubble expansion takes place for galaxies included to the local supercluster of galaxies, of the order of 70 Mpc scale, gravitationally unbounded. However, the local group of galaxies, to which our Galaxy belongs, of about 1.5 Mpc scale, already forms a gravitationally bound system, in which relative velocities differ considerably from the Hubble law. Therefore, in the local group, the value of α can be significantly less than the above value (4).

The total losses of particle energy are equal to

$$\frac{d\epsilon}{dt'} = -(1 + \epsilon) \exp(-\epsilon^{-1}) - a\epsilon(\epsilon_e^{-2} + b\epsilon_e^{0.6})^{-1} \exp(-\epsilon_e^{-1}) - \alpha\epsilon. \quad (5)$$

Although the value of α is small, the adiabatic energy losses become important for particles of not very high energies, $\epsilon_e < (\alpha/a)^{1/2} \simeq 2.7$, $E < 5.7 \cdot 10^{18} \text{ eV}$, when interaction with relict photons becomes not significant.

It should also be mentioned that in addition to relict photons in the intergalactic environment, there exists also the light from galaxies, and it contributes to the energy losses of cosmic rays. But, as shown by calculations, their contribution is small compared with that of the relict radiation (Aloisio, Berezhinsky & Grigorieva, 2013).

Let us introduce the dimensionless values of the power of sources and the distribution function, $Q'_i = Q_i L/c$, $N' = NL^3$. The dimensionless variables (with index i , which we omit further) will appear in the equation (1). We introduce also the variable τ instead of ϵ ,

$$\tau = \int_{\epsilon}^{\epsilon'} \frac{dx}{|d\epsilon/dt|_{\epsilon=x}}.$$

The value of τ is the time during which a particle loses its energy from the initial value ϵ' to the current one ϵ . As a result, Equation (1) will take the form

$$\frac{\partial}{\partial r} \left(\left| \frac{d\epsilon}{dt} \right| N \right) - \frac{\partial}{\partial \tau} \left(\left| \frac{d\epsilon}{dt} \right| N \right) = - \sum_i \frac{Q_i(\epsilon) \left| \frac{d\epsilon}{dt} \right|}{4\pi r_i^2} \delta(r - r_i). \quad (6)$$

Integrating equation (6) over r from 0 to r_m with the constant sum $r + \tau = \text{const}$, we get

$$N(r = 0, \epsilon) = \frac{1}{|d\epsilon/dt|} \sum_i \frac{Q_i(\epsilon_i) \left| \frac{d\epsilon}{dt} \right|_{\epsilon=\epsilon_i}}{4\pi r_i^2} + \frac{\left| d\epsilon/dt \right|_{\epsilon=\epsilon_m}}{|d\epsilon/dt|} N(\epsilon_m, r_m). \quad (7)$$

The value of r_m is the distance to which the approximation of rectilinear propagation is valid, $r_m \simeq 100 \text{ Mpc} / 13.7 \text{ Mpc} = 7.3$. The energy ϵ_m is determined by the ratio

$$r_m = \int_{\epsilon}^{\epsilon_m} \frac{dx}{|d\epsilon/dt|_{\epsilon=x}}.$$

In Equation (7) the first term is the contribution of the sources of cosmic rays of superhigh energies, located at distances $r < r_m$ from the Galaxy, whose particles

are observed in the Galaxy ($r = 0$). Because, according to analysis by Takami & Sato (2009), the density of such sources is of $10^{-2} - 10^{-4} Mpc^{-3}$, and the number of these sources in the sphere of radius r_m is significantly greater than unity, it is possible to go from the summation to the integration over volume, $4\pi \int_0^{r_m} r_i^2 dr_i$, introducing the average density of sources $\bar{q}(\epsilon)$. The value of energy, on which the quantity $\bar{q}(\epsilon)$ depends, is the initial energy of a particle, which overcomes the distance r_i from the source to the Galaxy, $\epsilon = \epsilon_i$,

$$r_i = \int_{\epsilon}^{\epsilon_i} \frac{dx}{|d\epsilon/dt|_{\epsilon=x}}.$$

However, at constant energy ϵ the distance r_i and the energy ϵ_i are connected, so the integration over r_i can be replaced by the integration over ϵ_i . The result is

$$\frac{1}{|d\epsilon/dt|} \sum_i \frac{Q_i(\epsilon_i) \left| \frac{d\epsilon}{dt} \right|_{\epsilon=\epsilon_i}}{4\pi r_i^2} = \frac{\int_{\epsilon}^{\epsilon_m} \bar{q}(\epsilon') d\epsilon'}{|d\epsilon/dt|}.$$

Thus, the distribution of cosmic rays of high energy, $E > 3 \cdot 10^{18} eV$, observed in the Galaxy, is largely determined by the loss function $|d\epsilon/dt|$ (5) in the intergalactic space, but not by the sources, distribution of which over energy $\bar{q}(\epsilon)$ is in average form.

2.2. Diffusive motion

In order to determine the contribution of distant ($r > r_m$) sources into the distribution of cosmic rays observed in our Galaxy (the second term in Equation (7)) we have to consider the diffusion region $r > r_m$. The equation for the distribution function $N(r, \epsilon)$ is

$$\frac{\partial}{\partial E} \left(\frac{dE}{dt} N \right) - \frac{D}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial N}{\partial r} \right) = \sum_i \frac{Q_i(E)}{4\pi r_i^2} \delta(r - r_i). \quad (8)$$

Here D is the coefficient of diffusion of cosmic rays in the intergalactic space. It, as well as in the Galaxy, depends on the particle energy. Let us suppose that this dependence is a power law, $D = D_0 E^\kappa$. For cosmic rays in the Galaxy $\kappa = 0.7$. Also as before, we introduce the dimensionless variables: the distances are measured in L , time - in L/c , the energy - in $4 \cdot 10^{20} eV$, the diffusion coefficient - in units of $D'_0 = D_0(4 \cdot 10^{20} eV)^\kappa / Lc$. We introduce also the effective time τ_D ,

$$\tau_D = \int_{\epsilon}^{\epsilon'} \frac{x^\kappa dx}{|d\epsilon/dt|_{\epsilon=x}}.$$

As a result, Equation (8) becomes

$$\frac{\partial}{\partial \tau_D} \left(\left| \frac{d\epsilon}{dt} \right| N \right) - \frac{D_0}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial}{\partial r} \left(\left| \frac{d\epsilon}{dt} \right| N \right) \right) = \epsilon^{-\kappa} \left| \frac{d\epsilon}{dt} \right| \sum_i \frac{Q_i(\epsilon)}{4\pi r_i^2} \delta(r - r_i). \quad (9)$$

Knowing the Green function of the equation of diffusion in a spherical region $0 < r < \infty$ (the diffusion approximation includes also the region $0 < r < r_m$ of the scale of the free path length),

$$G(r, r', t) = \frac{1}{(4\pi D_0 t)^{1/2}} \frac{r'}{r} \left\{ \exp\left[-\frac{(r - r')^2}{4D_0 t}\right] - \exp\left[-\frac{(r + r')^2}{4D_0 t}\right] \right\}, \quad (10)$$

integrating it with the right hand part of Equation (9) over r' and τ_D , then, as before, going from summation over i to the integration over r_i from r_m to infinity, introducing again the density of sources $\bar{q}(\epsilon)$, and transforming the integration over τ_D to the integration over ϵ' , we get

$$N(r_m, \epsilon) = \frac{1}{|d\epsilon/dt|} \int_{\epsilon}^{\epsilon_0} \bar{q}(\epsilon') \Phi \left[\left(\frac{r_m^2}{4D_0 \tau_D(\epsilon')} \right)^{1/2} \right] d\epsilon'. \quad (11)$$

Here the function $\Phi(y)$ is equal to

$$\Phi(y) = 2 - \frac{2}{\pi^{1/2}} \int_0^{2y} \exp(-z^2) dz + \frac{1}{\pi^{1/2}y} [1 - \exp(-4y^2)].$$

It varies monotonically from the value $\Phi = 2$ at $y = 0$ to $\Phi = 1$ for $y \gg 1$. And the fast transition of Φ to the value $\Phi \simeq 1$ occurs already at $y \simeq 2$ (see Figure 1). The typical value of y^2 is the ratio of the length of the mean free path length of particles r_m to the path L , travelling along which a particle loses a significant part of its energy, $y^2 \simeq r_m/L = 7.3$. In addition, large time τ_D , small y , corresponds to high initial energies of particle ϵ' . Because the source power $\bar{q}(\epsilon)$ decreases with energy, and, as we will see, rather fast, $\bar{q}(\epsilon) \propto \epsilon^{-2.7}$, then the contribution of the function $\Phi(y)$ at small values of its argument into the integral (11) is small. Thus, we can consider $\Phi \simeq 1$ in the expression (11). Altogether, the required distribution function of particles on the boundary of $r = r_m$ at $\epsilon = \epsilon_m$ equals

$$N(r_m, \epsilon_m) = \frac{1}{|d\epsilon/dt|_{\epsilon=\epsilon_m}} \int_{\epsilon_m}^{\epsilon_0} \bar{q}(\epsilon') d\epsilon'. \quad (12)$$

The value of ϵ_0 is the maximum energy of particles in sources.

3. Energy distribution of extragalactic particle observed in the Galaxy

Substituting the resulting distribution (12) into the expression (7), we obtain the sought distribution function of extragalactic cosmic rays, observed in the Galaxy,

$$N(r = 0, \epsilon) = \frac{\int_{\epsilon}^{\epsilon_0} \bar{q}(\epsilon') d\epsilon'}{|d\epsilon/dt|}. \quad (13)$$

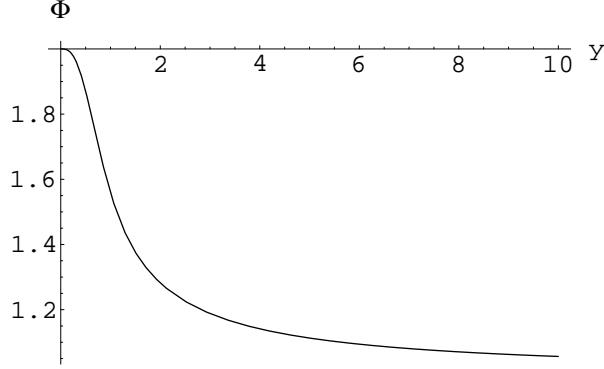


Figure 1: The function $\Phi(y)$ of the parameter $y = (r_m^2/4D_0\tau_D)^{1/2}$. See formula (11).

Equation (13) has a simple physical meaning: the particle flux in the energy space, $N|d\epsilon/dt|$, is equal to the total flux produced by sources Q_i . Moreover, since we have many sources, their fluxes are summing, ranging from close sources, providing a full range of energies from $\epsilon = \epsilon_{min}$ up to the maximum one $\epsilon = \epsilon_0$, to distant sources from which we observe only large initial energy $\epsilon \simeq \epsilon_0$. Suppose that the distribution $\bar{q}(\epsilon)$ is the power law function, $\bar{q}(\epsilon) = q_0\epsilon^{-\beta}$. Then the distribution function $N(\epsilon)$ is equal to

$$N(\epsilon) = \frac{q_0}{\beta - 1} \frac{\epsilon^{-\beta+1} - \epsilon_0^{-\beta+1}}{(1 + \epsilon) \exp(-1/\epsilon) + a\epsilon(\epsilon_e^{-2} + b\epsilon_e^{0.6})^{-1} \exp(-1/\epsilon_e) + \alpha\epsilon}. \quad (14)$$

The graph of the function $\epsilon^3 N(\epsilon)$ for $\epsilon_0 = 25$, $E_0 = 10^{22} eV$, and $\beta = 2.7$ is shown on Figure 2. One can see that at energies $E < 10^{18} eV$ and $E > 4 \cdot 10^{20} eV$ the distribution $N(\epsilon)$ is the power law, $N(\epsilon) \propto \epsilon^{-\beta}$. The same slope is observed at the intermediate energies, in the region of the maximum relative losses of energy, $(dE/dt)/E$, on the birth of electron-positron pairs, $E \simeq 10^{19} eV$. In the region $0.2 < \epsilon < 1$, N grows exponentially with decreasing of energy, $N(\epsilon) =$

$q_0 \epsilon^{-\beta+1} \exp(1/\epsilon)/(\beta-1)$. According to observations summarized by Berezhinsky (2013), the flux of particles $I(\epsilon) = cN(\epsilon)/4\pi$ in the energy range $6 \cdot 10^{18} eV < E < 4 \cdot 10^{19} eV$, $1.5 \cdot 10^{-2} < \epsilon < 0.1$, is indeed the power law function of energy with the index $\beta = 2.7$. When analyzing the data of observations it is convenient to use the function $\epsilon^3 N(\epsilon)$, which clearly describes the transition from Galactic distribution ($E^3 I(E) \propto E^{-0.1}$) for $E < 3 \cdot 10^{18} eV$ to the extragalactic one ($E^3 I(E) \propto E^{0.3}$) for $6 \cdot 10^{18} eV < E < 4 \cdot 10^{19} eV$. The function $\epsilon^3 N(\epsilon)$ has a maximum at $\epsilon = \epsilon_1 = 0.1$, $E_1 = 4 \cdot 10^{19} eV$ (see Figure 2). At energies $\epsilon > \epsilon_1$ the function $\epsilon^3 N(\epsilon)$ exponentially decreases not to zero, but to the minimum value at ϵ_2 , $\epsilon_2 \simeq 1$, $E_2 \simeq 4 \cdot 10^{20} eV$. After that the distribution $N(\epsilon)$ continues to fall down by a power law manner with the same index β , $N(\epsilon) \propto \epsilon^{-\beta}$. The fall down of the function $\epsilon^3 N(\epsilon)$ at energy ϵ_1 to its value at ϵ_2 is approximately one and half orders. The strong growth of the density of particles for $\epsilon < \epsilon_2$ is explained by the sharp decreasing of the rate of energy losses of particles when braking by relict photons becomes small. Here particles are accumulated. The distribution of $N(E)$ for energies $E > 4 \cdot 10^{20} eV$ does not go exponentially to small values that can seem as the result of the GZK effect. Here we observe that the distribution of $N(E)$ repeats the distribution of extragalactic sources $\bar{q}(E)$, unless of the maximum energy E_0 is not close to the energy $4 \cdot 10^{20} eV$. However, at energies $E > 4 \cdot 10^{20} eV$ the observational data have great uncertainty, which does not allow to make a conclusion about the growth of the function $E^3 N(E)$ at high energies $E > 4 \cdot 10^{20} eV$ under the condition $E_0 > 4 \cdot 10^{20} eV$. The energy range $E < 3 \cdot 10^{18} eV$ (see Figure 2), where the distribution $N(E)$ also

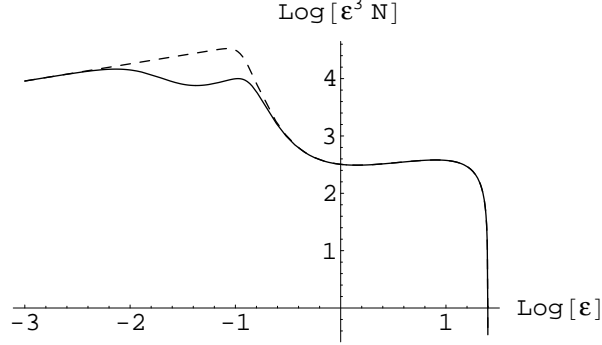


Figure 2: The function $\epsilon^3 N(\epsilon)$, $N(\epsilon)$ is given by the formula (14). Here we choose the value of maximum energy $E_0 = 10^{22} eV$, $\epsilon_0 = 25$, and the index $\beta = 2.7$. The dashed line represents this function when the electron-positron pairs production is absent.

reproduces the distribution of extragalactic sources $\bar{q}(E)$, is hidden by Galactic cosmic rays.

Estimate now the average power density of sources \bar{q} . Observations give the value of the extragalactic particle flux, where there is maximum value of product $E^3 I(E)$ at the energy $E_1 = 4 \cdot 10^{19} eV$,

$$I(E_1) = 4.7 \cdot 10^{-39} cm^{-2} s^{-1} sr^{-1} eV^{-1}.$$

Accordingly, the density of particles $N(E)$, $N(E) = 4\pi I(E)/c$, is

$$N(E_1) = 5.9 \cdot 10^{25} Mpc^{-3} eV^{-1}.$$

On the other hand, the dimensionless density of particles $N(\epsilon_1)$ and average power of sources $\bar{q}(\epsilon_1)$ are connected by the relation (14),

$$\bar{q}(\epsilon_1) = (\beta - 1) [(\epsilon_1^{-1} + 1) \exp(-1/\epsilon_1) + a(\epsilon_{e1}^{-2} + b\epsilon_{e1}^{0.6})^{-1} \exp(-1/\epsilon_{e1}) + \alpha] N(\epsilon_1) = 2 \cdot 10^{-2} N(\epsilon_1).$$

Bearing in mind that the dimensional quantity \bar{q} is $c/L = 7.1 \cdot 10^{-16} s^{-1}$ times less than the dimensionless one, we get

$$\bar{q}(E_1) = 8.4 \cdot 10^8 eV^{-1} s^{-1} Mpc^{-3}.$$

Considering that, as well as in our Galaxy, the power law spectrum with index $\beta = 2.7$ continues up to small energies $E_{min} \simeq 5 GeV$, we get

$$\bar{q}(E) = 8.4 \cdot 10^8 \left(\frac{E}{4 \cdot 10^{19} eV} \right)^{-2.7} eV^{-1} s^{-1} Mpc^{-3}. \quad (15)$$

The total average power density of extragalactic sources $\mathcal{E} = \int_{E_{min}}^{E_0} \bar{q}(E) E dE$ is equal to

$$\mathcal{E} = 1.8 \cdot 10^{43} \left(\frac{E_{min}}{5 GeV} \right)^{-0.7} erg s^{-1} Mpc^{-3}. \quad (16)$$

This value divided by the density of galaxies, $N_g \simeq 1 Mpc^{-3}$, at least two orders of magnitude exceeds the power of the Galaxy in cosmic rays, $10^{41} erg s^{-1}$. If we assume that the sources of ultrahigh energy particles are active galactic nuclei with relativistic jets generated inside, the power of which is $(10^{45} - 10^{46}) erg s^{-1}$ (Mao-Li, et al., 2008), then their density in the Universe is of $N_g \simeq (10^{-2} - 10^{-3}) Mpc^{-3}$. The same estimation of the density of extragalactic sources of cosmic rays follows also from the conditions of isotropy of arrival of particles in the range of energies $E \simeq 10^{19} eV$ (Abbasi et al., 2004).

4. Galactic cosmic rays

The most surprising fact, following from the previous consideration, is that the spectrum of the power density of extragalactic cosmic rays (15) has the

the same slope that have Galactic cosmic rays density before the 'knee', $E < 3 \cdot 10^{15} \text{eV}$, $\beta = 2.7$. Let us note here that the cosmic rays power density $\bar{q}(E)$ understanding as the average power radiated by a galaxy as a whole is proportional to the density of cosmic rays in a galaxy $N(E)$, $\bar{q}(E) \propto N(E)Sc$, where the value of S is the galactic surface radiated cosmic rays. This indicates that the nature of the origin of cosmic rays in the Galaxy and in active galactic nuclei is the same. The formation of the spectrum with index $\beta = 2.7$ in the Galaxy is explained by the fact that the index of the power law energy spectrum of source is of universal value of $\beta = 2$. This is valid as for the acceleration of particles on fronts of strong shock waves (Krymskii, 1977; Bell, 1978), as for the acceleration at the base of the jets emitted near massive black holes in centers of galaxies (Istomin, 2014). Next, accelerated particles, spreading over a galaxy, are scattered by inhomogeneities of a magnetic field. Their motion becomes diffusive. Moreover, the coefficient of diffusion is larger for particles with larger energies, $D \propto E^{0.7}$ (Ptuskin, 2007). The density of particles is equal to the product of the power of a source Q to the lifetime of particles τ , $N = Q\tau$. The lifetime is the time of escape of particles from a galaxy, $\tau = R^2/D$, R is the radius of a galaxy. Thus, $N(E) \propto E^{-2-0.7}$. There arises the question: why in our Galaxy the spectral index of cosmic rays at energies $E > 3 \cdot 10^{15} \text{eV}$ deviates from the value of $\beta = 2.7$? Spectrum becomes softer, $\beta = 3.1$. If the source of cosmic rays in a galaxy is strong shock waves from supernova explosions, it is not clear why the spectrum of high energy particles from active galaxies remains with index $\beta = 2.7$ up to energies $\sim 10^{20} \text{eV}$. More

natural to assume that the source of cosmic rays is a jet emitted from active galactic nucleus and whose power significantly exceeds the power transformed to particles by supernova explosions. Istomin (2014) suggested that Galactic cosmic rays were produced by the jet, emitted from the center of the Galaxy. Giant bubbles of relativistic gas, observed above and below the Galactic plane, are remnants of this bipolar jet existed previously. From the size of the bubbles it follows that the jet switched on $2.4 \cdot 10^7$ years ago, and it worked at least 10^7 years. Thus, before the jet switched off the Galaxy and its halo were uniformly filled by cosmic rays with the spectral index $\beta = 2.7$ (Istomin, 2014). After the source turned off particles continue to flow out from the Galaxy, and their density begins to decrease with time. Consider how it is happen.

Suppose that at time $t = 0$ cosmic rays with density $N_0(E)$ uniformly filled the spherical region (Galaxy and halo) of radius R . Then, assuming that the motion of particles is of diffusion character, using the Green function (10), we find the density of cosmic rays $N(r, E, t)$ at the point located at distance r from the center of the Galaxy and at the time t , $N(r, E, t) = N_0(E)F(p, r)$,

$$F(p, r) = \frac{1}{\pi^{1/2}} \left\{ \frac{R}{2rp} [\exp[-p^2(1 - r/R)^2] - \exp[-p^2(1 + r/R)^2]] + \int_{-p(1-r/R)}^{p(1+r/R)} \exp(-y^2) dy \right\}, \quad (17)$$

where the parameter p is equal to $p(E, t) = [R^2/4D_g(E)t]^{1/2}$. For small values of p , $p \ll 1$, the function F is equal to $F = 4p/\pi^{1/2}$, for large values $p \gg 1$, $F = 1$. The graph of the function $F(p)$ for two different values of $r = R/2$ and $r = 0$ are presented on the Figure 3. It is seen that the transition of density

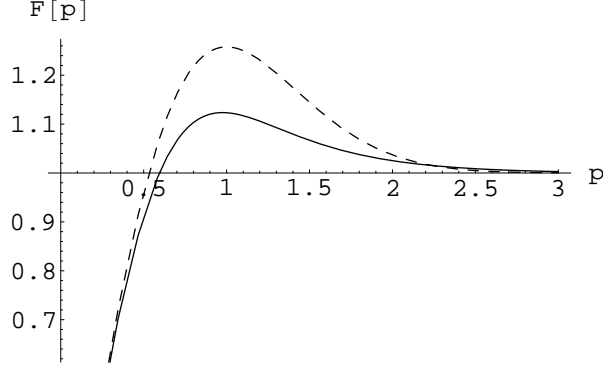


Figure 3: The function $F(p)$. The solid line corresponds to $r = R/2$, the dashed line - $r = 0$

of cosmic rays from the initial distribution N_0 ($p > 1$) to the falling down with time, $N = N_0(4R^2/\pi D_g t)^{1/2}$, takes place at $p \simeq 1$. At this point there is a transition of the spectrum of cosmic rays from the original, $N \propto E^{-2.7}$, with energies $E < E_k$ to the distribution of $N \propto E^{-2.7-0.7/2} = E^{-3.05}$ for $E > E_k$. The value of energy E_k is defined by the equality $p = 1$, $D_g(E_k) = R^2/4t$. In the center of the Galaxy ($r = 0$) the transition occurs exactly at the point $p = 1$, for us ($r \simeq R/2$), this point is also very close to unity. When $p = 1$ there is a local increase of density of cosmic rays, i.e. near energies $E \simeq E_k$ the distribution $N(E)$ is really observed as 'knee' (see Fig. 4). The position of the 'knee' depends on the time t , passed after turning off of the source. Knowing the position of the 'knee' at the present time $t = t_0$, we find

$$t_0 = \frac{R^2}{4D_g(E_k)} = 4.2 \cdot 10^4 \left(\frac{R}{5 \cdot 10^{22} \text{cm}} \right)^2 \left(\frac{D_g(1 \text{GeV})}{2.2 \cdot 10^{28} \text{cm}^2 \text{s}^{-1}} \right)^{-1} \left(\frac{E_k}{3 \cdot 10^{15} \text{eV}} \right)^{-0.7} \text{year}.$$

It should be noted that 'knee' is moving with time, $E_k = 3 \cdot 10^{15} (t/t_0)^{-1.43} \text{eV}$.

The speed is now equal to $dE_k/dt = -1.43 E_k/t_0 = -10^{11} \text{eV/year}$.

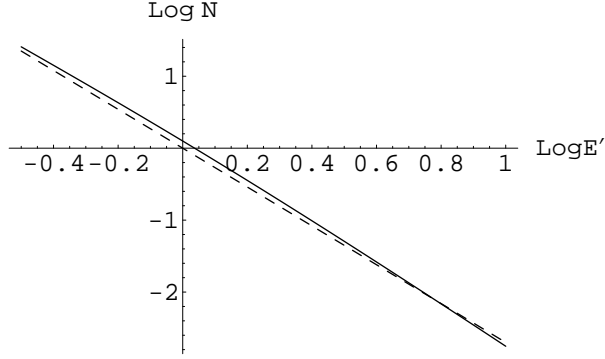


Figure 4: The distribution of Galactic cosmic rays $N(E) \propto E^{-2.7} F(p)$ over energy E near the 'knee' at the point $r = R/2$, $E' = E/E_k$. The function $F(p)$ is defined by the expression (17). The dashed line is the dependence $N(E) \propto E^{-2.7}$.

5. Conclusions

We showed that the distribution of power of sources of extragalactic cosmic rays in the energy range of $3 \cdot 10^{18} eV < E < 10^{21} eV$ is a power law, $\bar{q}(E) \propto E^{-2.7}$. Thus, it is the same as in our Galaxy at the energy range below the 'knee', $E < 3 \cdot 10^{15} eV$. This indicates the common nature of the origin of cosmic rays in the Galaxy and in other galaxies. However, the power of extragalactic sources at least two orders of magnitude exceeds the capacity of the Galaxy (see formula (16)). The conclusion from this is that a 'normal' galaxy, to which belongs our Galaxy, is not the source of cosmic rays. The estimation of the density of extragalactic cosmic rays sources, $N_g \simeq 10^{-2} - 10^{-3} Mpc^{-3}$, indicates galaxies with active nuclei. The possible source of energetic charged particles is relativistic jets emitted from surroundings of massive black holes. Thus, acceleration by shock waves from supernova explosion is not possible to explain

the origin of cosmic rays up to energies $\simeq 10^{18}eV$. Otherwise, all galaxies in more or lesser degree would be sources of cosmic rays, because in all of them there are explosions of supernova. Why, nevertheless, we observe cosmic rays in the Galaxy is explained that once in the past the Galaxy was also active. From the center of the Galaxy there emitted the relativistic bipolar jet, the remnants of which is observed now above and below the Galactic plane as bubbles of relativistic gas (Su, Slatyer & Finkbeiner, 2010). Due to the fact that now this source of cosmic rays in the Galaxy is not working, it appears the deflection of the spectrum of Galactic cosmic rays from dependence $N(E) \propto E^{-2.7}$ in the whole energy range. For $E > 3 \cdot 10^{15}eV$, the spectrum becomes softer, $N(E) \propto E^{-3.1}$. This is because particles, that once filled the Galaxy, leave it the faster the larger their energy, because their diffusion coefficient increases with energy, $D \propto E^{0.7}$. Particles of larger energies quickly leave the Galaxy than particles less energies. For the diffusive motion of particles $N(E) \propto N_0(E)(Dt)^{-1/2} \propto E^{-2.7-0.7/2}$ for energies $E > E_k$ and $N(E) \simeq N_0(E)$ for energies $E < E_k$, where $N_0(E)$ is the initial distribution of particles. Thus, the 'knee' formation reflects the escape of particles from the Galaxy. Knowing the position of the 'knee' now one can estimate the time when the source of cosmic rays in the Galaxy stopped, it occurred $4.2 \cdot 10^4$ years ago. The position of the 'knee' is not constant in time, it must move, $E_k \propto t^{-1.43}$. This motion one can notice if to have a sufficient accuracy of the measurement of the 'knee' position. During 50 years the change in the position of the 'knee' is $\Delta E_k = -5 \cdot 10^{12}eV$.

Aknowlegements

Author thanks V. Berezhinsky for the fruitful discussions.

This work was done under support of the Russian Foundation for Fundamental Research (grant numbers 14-02-00831 and 13-02-12103).

References

- [1] Abbasi, R.U., et al., 2004, *Astrophys. J.*, 610, L73.
- [2] Aloisio, R., Berezhinsky, V., Grigorieva S., 2013, *Astropart. Phys.*, 41, 73,94.
- [3] Auger Collaboration, 2007, *Science*, 318, 939.
- [4] Bell, A.R., 1978. *MNRAS*, 182, 147.
- [5] Berezhinsky, V., Gazizov, A., Grigorieva, S., 2006, *Phys. Rev. D*, 74, 043005.
- [6] Berezhinsky, V., 2013, *EPJ Web of Conference*, 53, 01003.
- [7] Berezhinsky, V., 2014, *Astropart. Phys.* 53, 120.
- [8] Greizen, K., *Phys. Rev. Lett.*, 1966, 16, 748.
- [9] Istomin, Ya.N., 2014. *New Astronomy*, 27, 13.
- [10] Krymskii, G.F., 1977. *Soviet Physics-Doklady*, 22, 327.
- [11] Mao-Li, M., Xin-Wu, C., Dong-Rong, J, Min-Feng, G., 2008. *Chin. J. Astron. Astrophys.*, 8, 39.49.
- [12] Ptuskin, V.S., 2007, *Phys. Uspechi*, 50, 534.

- [13] Stanev, F., Engle, R., Mucke, A., Protheroe, R.J., Rachen. J.P., 2000, Phys. Rev. D, 62, 093005.
- [14] Su, M., Slatyer, T.R., Finkbeiner, D.P., 2010. Astrophys. J., 724, 1044.
- [15] Takami, H., Sato, K., 2009, Astropart. Phys, 30, 306.
- [16] The Pierre Auger Collaboration, 2008, Astropart. Phys., 29, 188.
- [17] The Pierre Auger Collaboration, arXiv. 1009.1855., 2010.
- [18] Zatsepin, G.T., Kuz'min, V.A., 1966, JETP Letters, 4, 78.